

# Heat transfer and thermally induced stresses in window glass coated with optically active nano-particles

A thesis presented for the degree of  
Masters in Engineering

By

Humayer Ahmed Chowdhury

Institute of Nanoscale Technology  
Faculty of Engineering  
University of Technology, Sydney

May 2007

## Declaration of original authorship



---

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that I am the primary and original author of this thesis, and any help I have received in my research work and its preparation has been acknowledged. In addition, I certify that all literature sources are cited and listed in the references of this thesis.

A handwritten signature in black ink, appearing to read 'Humayer', written over a dotted line.

Humayer Ahmed CHOWDHURY

19/6/07

Date

## Acknowledgements

---

I acknowledge the continuous support and assistance of my principal supervisor Professor Mike B Cortie and co-supervisor Dr. Phuoc Huynh towards the completion of the thesis. I also thank VKOOL, Pilkington and Mant Glass Wollongong for kindly supplying test materials, and AngloGold Ashanti Australia Limited for partial support.

# Table of contents

---

Declaration of original authorship.....	i
Acknowledgement.....	ii
Table of contents.....	iii
List of figures.....	vi
List of tables.....	ix
Symbol Index – Nomenclature.....	x
Abstracts.....	xiii
 CHAPTER I – Introduction	 1
 CHAPTER II - Literature review	
2.1. Background	
2.1.1. Thermal radiation spectrum	7
2.1.2. Optical performance of coated glass	8
2.1.3. Phong's law	9
2.2. Heat transfer	
2.2.1. Heat transfer through glass windows	10
2.3. Window glazing systems	
2.3.1. Clear glass and its optical properties	12
2.3.2. Conventional solar glazing	12
2.3.3. Clear solar control glazing	13
2.3.4. Other types of glazing	
2.3.4.1. Antireflective glazing	14
2.3.4.2. Photocatalytic glazing	15
2.3.4.3. Variable transmission glazing	16
2.3.5. Solar glazing based on gold nano-particles	18

2.4. Properties of window glazing	
2.4.1. Solar thermal properties	19
2.5. Advantages and disadvantages associated with window glazing systems	
2.5.1. Advantages	20
2.5.2. Disadvantages	21
2.6 Opportunities in window glazing	21
CHAPTER III – Experimental set-up	
3.1. Physical model	22
3.2. Heat balance across the window	23
3.3. Apparatus for determining energy balance	25
3.4. Materials included in the test matrix	
3.4.1. Standard materials	27
3.4.2. Coating of glass panes at UTS	27
3.5 Measurements	29
CHAPTER IV – Results	
4.1. Heat transfer across glass	34
4.2. Solar Heat Gain Coefficient (SHGC)	36
4.3. Energy balancing for experimental coatings	39
CHAPTER V – Thermal stresses in window glasses	
5.1. Introduction	41
5.2. Structural behaviour of the glass	
5.2.1. Basic crystalline structure of the glass	41
5.2.2. Strain on the glass	42
5.3. Thermal expansion coefficient	43
5.4. Estimation of thermally induced stress	44
5.5. Fracture mechanics	
5.5.1. Fast fracture and crack development	47
5.5.2. Crack velocity	49
5.5.3. Factors influencing the glass thermal stress	50

CHAPTER VI – Finite Element Analysis	
6.1. Introduction	52
6.2. Results	
6.2.1. The determination of surface temperature	54
6.2.2. Case study: door-shaped glass panel	55
CHAPTER VII – Conclusions	60
REFERENCES	61
APPENDICES	
1. Appendix A – Detail specifications of the flux sensor	66
2. Appendix B – Total energy received by the glass pane	67
3. Appendix C – Total energy transmitted	68
4. Appendix D – Phong’s illumination model	69
5. Appendix E – Determination of heat transfer coefficient $h$	70
6. Appendix F – Heat transfer coefficient of various glazing systems	71
7. Appendix G – Energy convected from front and back faces of the glass pane	72

## List of Figures

- 
- Figure 1. Characteristics of the ideal window in (a) cooling-dominated building (b) heating-dominated building
- Figure 2. Thermal radiation portion of the electromagnetic spectrum
- Figure 3. Scattering parameters for transmission and reflection of the glass
- Figure 4. Specular reflection
- Figure 5. Three modes of heat transfer through a window
- Figure 6. Spectral characteristics of selective film
- Figure 7. Transmittance behaviour of anti-reflective coated vs. uncoated glass
- Figure 8. Transmission of  $\text{TiO}_2$  film obtained from a  $\text{TiO}_2$ -sol
- Figure 9. Visible light transmission through variable transmission window system vs. various other glazing systems as a function of total energy transmission
- Figure 10. Various modes of solar thermal properties using a model film at same solar direct transmittance but different reflectance/absorption ratio ( $R/A$ )
- Figure 11. Physical model of glass with solar control coating system
- Figure 12. Energy balance in the glass
- Figure 13. (a) Schematic representation of experimental set-up, (b) Photograph - Measurement of radiant heat transfer through coated glass panes.
- Figure 14. Spectral characteristics compared of (a) incandescent lamps used, (b) ASTM's AM 1.5 solar spectrum, (c) CIE/ISO Illuminant A and, (d) black body at 2800K
- Figure 15. a) and b) High resolution scanning electron microscopy images of coatings on sample *Au-1* and sample *Au-2* respectively showing a distribution of nano-sized gold hemispheres of ~30 nm diameter and c) slides with range of coating colors (photo courtesy of Mr X. Xu).
- Figure 16. Measurement of incident radiation from the regions mapped onto the pane
- Figure 17. Measurement of radiation that was specularly and diffusively emitted from back face

- Figure 18. Measurement of radiation that was specularly and diffusively emitted from front face
- Figure 19. Empirical model for diffusively emitted radiation from the front surface of a plain glass sheet, showing how the emission,  $D_{0,0}$ , normal to the plane of glass was estimated by extrapolation.
- Figure 20. Transmission as a function of wavelength for commercial glasses XL121 and V<sub>k</sub>40. Data are from the manufacturer's pamphlets
- Figure 21. Transmission characteristics of two gold coated panes (*Au-1* and *Au-2*). The spectrum of ordinary window glass is also shown. Data are from X. Xu and the literature.
- Figure 22. Energy balance for a) 6mm XL121 laminated heat absorbing glass b) 3mm V<sub>kool</sub> 40<sup>TM</sup> heat reflective glass c) 3mm glass coated with gold nano-particles.
- Figure 23. Silicon-oxygen tetrahedron bond
- Figure 24. Schematic of various types of strain showing change in length, shape or volume
- Figure 25. Thermal Expansion Coefficient for different glass substrates
- Figure 26. Thermal Stress Factor chart redrawn from "A method of evaluation for thermal stress in monolithic annealed glass", written by Lingnell AW and Beason L in the 2003 Glass Processing Days Conference Proceedings in Finland
- Figure 27. Probability of Breakage chart redrawn from "A method of evaluation for thermal stress in monolithic annealed glass", written by Lingnell AW and Beason L in the 2003 Glass Processing Days Conference Proceedings in Finland
- Figure 28. Crack propagation in the glass substrate
- Figure 29. Crack propagation length as a function of applied stress
- Figure 30. Crack velocity versus stress intensity factor
- Figure 31. Cracking observed in laminated glass door that included an absorptive solar film in its structure.
- Figure 32. Temperature of the glass surface as a function of absorbed heat showing surface temperatures of various experimental glazing systems, under a flux of 500 W/m<sup>2</sup> of tungsten lamp illumination



Figure 33. a) Temperature distribution in kelvin scale, b) Contour diagram showing  $\sigma_y$  developed in glass door subjected to illumination at  $200\text{W/m}^2$  on its lower half, while being rigidly fixed top and bottom to an infinitely stiff support.

Figure 34. Maximum compressive stress developed in centre of glass door set at top and bottom into a rigid support, as a function of heat load.

Figure 35. Contour diagram showing principal stress  $\sigma_1$  developed in the glass door when subjected to heat load of  $200\text{W/m}^2$  on its lower half, while being rigidly fixed only along its lower edge.

Figure 36. Maximum tensile stresses developed along edges of glass door fixed only at its base, as a function of heat load.

Figure 37. Maximum allowable stress as a function of crack size in glass.

## List of Tables

- 
- Table 1. Energy balance for a 29 watt heat load with tungsten 2800K radiation applied to a variety of glazing systems at intensity of  $500 \text{ W/m}^2$ . The standard error on values of  $D_{0,0}$  is  $<0.1 \text{ W}$  for all except sample  $V_{\text{KOOL}} 40$ . The energy balance is accurate to within  $1.2 \text{ W}$  (4%).
- Table 2. Performance data provided by the material suppliers for performance in sunlight compared to the proportion of total energy transmitted by the test samples (Solar Heat Gain Coefficient) using the Illuminant A spectrum. Transmittance data have an accuracy of  $\pm 1\%$ .
- Table 3. Material properties used for basic 3 mm glass

## Symbol Index - Nomenclature

English Letters	
$A$	Area of the glass, $m^2$
$c_p$	Specific heat
$D_{r,\theta}$	Diffusely emitted radiation as a function of distance, $r$ and angle, $\theta$
$D_{0,0}$	Surface intensity of radiation reflected perpendicularly from glass surface
$E$	Modulus of elasticity (Young Modulus)
$E_\lambda$	Spectral irradiance of the light source, $W.m^{-2}.nm^{-1}$ , as $f(\lambda)$
$F$	Proportion of incident radiant energy transferred to the interior of the glass
$Gr_L$	Grashof number
$h$	Convective heat transfer coefficient, $W.m^{-2}.K^{-1}$
$I_\lambda$	Maximum specular reflectance
$k$	Thermal conductivity $W.m^{-1}.K^{-1}$
$K_c$	Stress intensity
$l_0$	Length at 273K
$l_t$	Length at temperature $t$
$l$	Mode of the resonance ( $l=1$ produces a dipole resonance, $l=2$ a quadrupole resonance, $l=3$ a octupole resonance)
$L$	Height of the glass pane, $m$
$m$	Parameter accounting for decrease in $D_{r,\theta}$ as $f(r)$
$n$	Specular reflection exponent in Phong's Law
$Nu_L$	Nusselt number
$Pr$	Prandtl number
$q$	Heat transfer through or from glass surface, $W$
$q_c$	Convected heat energy
$q_i$	Incident heat energy
$q_r$	Heat energy radiated
$Ra$	Rayleigh number

$R_{sol}$	Proportion of the total solar irradiance that is reflected
$T_o$	Outside temperature
$T_i$	Inside temperature
$T_{air}$	Temperature of laboratory air, K
$T_f$	Film temperature K
$T_s$	Temperature of the glass surface, K
$T_{vis}$	Proportion of visible spectrum that is directly transmitted by glass
$T_{sol}$	Proportion of the total solar irradiance that is transmitted
$T_\lambda$	Total spectral transmissivity of the glass, as $f(\lambda)$
$V_\lambda$	Photo-optic luminous efficiency function of the human eye, as $f(\lambda)$
$x$	Ratio of the inner and outer radii of a nano-shell particle
Greek Symbols	
$\alpha$	Thermal expansion co-efficient 1/°C
$\beta$	Volumetric coefficient of thermal expansion 1/°C
$\epsilon$	Emissivity
$\gamma$	Angular deviation from specular reflection
$\nu$	Poisson's ratio
$\rho$	Density kg/m <sup>3</sup>
$\epsilon'_{Au}(\lambda)$	Real part of the dielectric constant of gold, as $f(\lambda)$
$\epsilon'_m(\lambda)$	Real part of the effective dielectric constant of the matrix surrounding the gold nanoparticle, as $f(\lambda)$
$\theta$	Angle between axis of radiation sensor and surface of glass
$\lambda$	Wavelength of light, nm
$\sigma_{thermal}$	Thermal stress
$\phi$	Volume fraction of gold particles lying on the surface of the glass
$\omega_{l-}$	Energy of symmetrically coupled plasmons on the inner and outer surfaces of the metal shell, eV
$\omega_s$	Surface plasmon energy of a solid nanoparticle, eV
Subscripts	
$a$	Quantities associated with air
$b, back$	Back face of the glass
$conv$	Convective quantities

$f$	Front face of the glass
$rad$	Radiation quantities
$solar$	Solar quantities
Acronyms and abbreviations	
ASTM	American Society for Testing and Materials
$ADF_t$	Angular Distribution Function of transmittance
$ADF_r$	Angular Distribution Function of reflectance
CIE	International Commission on Illumination
E971	Standard Practice for Calculation of Photometric Transmittance and Reflectance of Materials to Solar Radiation.
FEA	Finite Element Analysis
G159	Standard Tables for References Solar Spectral
$H_t$	Haze parameters of transmission
$H_r$	Haze parameters of reflectance
ISO	International Organisation for Standardization
Kc	Fracture toughness
POB	Probability of Breakage
$Q_{convected}$	Energy convected
$R_{dif}$	Diffusively reflectance of energy
$R_{tot}$	Total energy reflectance
SC	Shading Coefficient
SL	Solar Load
SHGC	Solar Heat Gain Coefficient
$T_{dif}$	Diffusively transmittance energy
$T_{tot}$	Total energy transmittance
TOMS	Tetraalkoxysilanes
$TiO_2$	Titanium dioxide
TSF	Thermal Stress Factor
U	Total heat transfer coefficient

## Abstract

---

Reflective or absorptive coatings for solar control on windows are popular in the architectural and automotive industries. In general, noble metal coatings have been used in reflective applications, and various heat-absorbing dielectric compounds in absorptive ones. The ultimate objective is to moderate incoming infra-red radiation while simultaneously preserving the desirable transparent nature of the window. In addition, one problem with merely absorbing infra-red radiation by the glazing system is that the coating and hence the surface of the special glass becomes very hot. This increased glass temperature will result in thermal stresses leading to an expansion of the glass, which, if not matched by an expansion of the window frame, can cause buckling and cracking. The objective of this project has been to study heat transfer from and through glass surfaces to which IR-screening surface coatings have been applied, and to model the distribution of the resulting thermally-induced stresses in the glass.

The use of coatings of gold nano-particles in an absorptive role has hardly been considered previously. The present study explores the characteristics of such coatings by subjecting panes of various experimental and commercially available glasses to illumination by an array of incandescent lamps at  $500 \text{ W/m}^2$ , which is a representative figure for a vertical east- or west-facing window in Sydney, Australia or Houston, USA, during March and September. The heat transfer through the samples was determined and used to guide the subsequent finite element analysis. This provided an indication of the thermally induced stresses developed on the glass surfaces due to heat released by the absorptive coatings.